

Polarization Observables in ϕ Meson Photoproduction and the Strangeness Content of the Proton

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Abstract

The contributions of direct knockout processes, in addition to the diffractive production and one-pion-exchange processes associated with the $\phi\rho\pi$ and $\phi\gamma\pi$ couplings, to the polarization observables of the ϕ photoproduction from proton are calculated. We make use of Pomeron-photon analogy and a relativistic harmonic oscillator quark model. We find that some of the double polarization observables are very sensitive to a possible $s\bar{s}$ admixture in the proton. It arises from the difference in the spin structures of the three different amplitudes. This suggests that such measurements could be very useful to probe the strangeness content in the proton.

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Essentially all the constituent quark models which give good description of the low energy properties of baryons treat nucleon as consisting of only up and down quarks. It naturally comes as a big surprise when some recent experiments and theoretical analyses indicate a possible existence of a non-negligible strange quark content in the proton. For example, measurements of the nucleon spin structure functions [1] indicate that the amount of spin carried by the strange quark pairs $s\bar{s}$ is comparable to that carried by the u and d quarks and polarized opposite to the nucleon spin. A similar conclusion has been drawn from the BNL elastic νp scattering [2]. Analyses of the πN sigma term [3] also suggest that proton might contain an admixture of 20% strange quarks. Recently, experiments on annihilation reactions $\bar{p}p \rightarrow \phi X$ ($X = \pi^0, \eta, \rho^0, \omega, \gamma$) at rest [4] show a strong violation of the OZI rule [5]. Again, the presence of an $s\bar{s}$ component in the nucleon wave function would enable the direct coupling to the ϕ meson in the annihilation channel without violating the OZI rule [6,7]. However, it has also been argued that such experimental results could be understood with little or no strangeness in the nucleon [8,9]. Resolution of this question will provide us with important insight to improve current hadron models. It would be hence important and interesting to look into other possible clear signal [10] that might be related directly with the strangeness content of nucleon.

In the lepto- and photo-production of ϕ meson from proton of Fig. 1(a), in addition to the diffractive production of vector-meson dominance model (VDM) depicted in Fig. 1(b), an $s\bar{s}$ admixture in the nucleon wave function, if exists, can contribute to the process through the direct “knockout” mechanism of Fig. 1(c,d). We use $p = (E_p, \mathbf{p})$, $p' = (E'_p, \mathbf{p}')$, $q = (\nu, \mathbf{q})$, and $q_\phi = (E_\phi, \mathbf{q}_\phi)$ to denote the four-momenta of the target and recoil proton, photon beam, and produced ϕ meson in the laboratory frame, respectively. The corresponding variables in c.m. system will be distinguished by an asterisk as p^* , p'^* , q^* , and q_ϕ^* . In Ref. [11], this idea was applied to ϕ electroproduction with a non-relativistic quark model, and the calculation was improved in Ref. [12] by including relativistic Lorentz-contraction effects. With the form factors and overlap integrals evaluated with a relativistic harmonic oscillator quark model [13], it was found that with less than 5% admixture of strange sea quarks in the proton, the cross section of the direct knockout mechanism is comparable to that of VDM for electroproduction at moderately large electron four-momentum transfer. However, it is not easy to disentangle the two mechanisms from the cross section measurement because their respective contributions have similar dependence on the momentum transfer [12].

In this Letter, we propose that measurements of polarization observables of ϕ meson photoproduction could offer a possible clean signature of the strangeness content of nucleon. Based on the model of Ref. [12], we will show that some of the double polarization observables are very sensitive to the hidden strangeness content of proton, even with less than 1% admixture of $s\bar{s}$ component in the proton wave function. This is because the contributions from the direct knockout and the diffractive processes to these observables have very different spin (helicity) dependence.

The diffractive ϕ photoproduction mechanism of VDM assumes that the incoming photon mixes into the ϕ meson and then scatters diffractively with proton through the exchange of a Pomeron [14]. Experimental observations for the vector meson production, small- $|t|$ elastic scattering, and diffractive dissociation indicate that the Pomeron behaves rather like an isoscalar photon-like particle. A microscopic description of the vector-meson photoproduction at high energy based on the Pomeron-photon analogy was proposed by Donnachie and

Landshoff [15], and the Pomeron could be described successfully in terms of non-perturbative two gluon exchange [15–18]. With the use of the spin structure of the diffractive ϕ photo-production mechanism of these models, the invariant amplitude of the diffractive production reads

$$\begin{aligned} T_{fi}^{\text{VDM}} &= i T_0 \bar{u}(p') \gamma_\alpha u(p) \varepsilon_\mu^*(\phi) \Gamma^{\alpha, \mu\nu} \varepsilon_\nu(\gamma), \\ \Gamma^{\alpha, \mu\nu} &= (q + q_\phi)^\alpha g^{\mu\nu} - q^\mu g^{\alpha\nu} - q_\phi^\nu g^{\alpha\mu}, \end{aligned} \quad (1)$$

where T_0 includes the dynamics of Pomeron-hadron interaction and is taken to be real [19]; $\varepsilon_\mu(\phi)$ and $\varepsilon_\mu(\gamma)$ are the polarization vectors of ϕ meson and photon, respectively, and $u(p)$ is the proton Dirac spinor. The spin structure of the amplitude T_{fi}^{VDM} is the same as that of a one-photon-exchange amplitude [20]. T_0 is determined by fitting the data in the form of $(d\sigma/dt)_{\text{VDM}} = \sigma_\gamma(W) b_\phi \exp(-b_\phi |t - t_{\text{max}}|)$ as in Ref. [21] with $b_\phi = 4.01 \text{ GeV}^{-2}$ and $\sigma_\gamma(W) = 0.2 \text{ } \mu\text{b}$ around $W = 2 \text{ GeV}$, where $t = (p - p')^2$ and $W^2 = (p + q)^2$.

At relatively low photon energy, one-pion-exchange (OPE) diagrams of direct ϕ photo-production as shown in Fig. 2 also contribute [14]. It may be interpreted as a correction to the VDM process [22]. It is straightforward to write down the amplitudes of the OPE diagrams of Fig. 2. They have an identical form and we may write their sum as

$$\begin{aligned} T_{fi}^{\text{OPE}} &= \frac{i}{t - m_\pi^2} g_{NN\pi} \tilde{g}_{\phi\gamma\pi} \bar{u}(p') \gamma_5 u(p) \\ &\quad \times \epsilon^{\mu\nu\alpha\beta} q_{\phi,\mu} q_\alpha \varepsilon_\nu^*(\phi) \varepsilon_\beta(\gamma), \end{aligned} \quad (2)$$

where $\tilde{g}_{\phi\gamma\pi}$ is the effective coupling constant determined from the branching ratio of $\phi \rightarrow \gamma\pi$ and m_π is the pion mass. We also include the Benecke-Dürr form factors for each vertex as given in Ref. [22].

The main ingredient of the knockout photoproduction mechanism is the assumption that the constituent quark wave function of proton, in addition to the usual 3-quark (uud) component, contains a configuration with explicit $s\bar{s}$ -pair. A simple realization of this picture is the following wave function in Fock space [11]

$$\begin{aligned} |p\rangle &= A|[uud]^{1/2}\rangle + B\left\{a_0|[[uud]^{1/2} \otimes [s\bar{s}]^0]^{1/2}\rangle \right. \\ &\quad \left. + a_1|[[uud]^{1/2} \otimes [s\bar{s}]^1]^{1/2}\rangle\right\}, \end{aligned} \quad (3)$$

where B^2 is the strangeness admixture of the proton and (a_0^2, a_1^2) are the fraction of the $s\bar{s}$ pair with spin 0 and 1, respectively. The superscripts represent the spin of each cluster and the circle-cross represents the vector addition of spins of uud and $s\bar{s}$ clusters and their relative orbital angular momentum ($\ell = 1$). Details on the wave functions in the relativistic harmonic oscillator model [13] and electromagnetic current associated with the ϕ photo- and electro-production can be found in Refs. [11,12].

We classify the knockout mechanism into $s\bar{s}$ - and uud -knockout depending on the struck quark by the photon. The knockout amplitudes are most easily evaluated in the laboratory frame with the use of wave function (3) as presented in Ref. [12]. After transformation into c.m. frame, we have

$$\begin{aligned}
T_{m_f, m_\phi; m_i, \lambda_\gamma}^{s\bar{s}} &= i T_0^{s\bar{s}} \mathcal{S}_{m_f, m_\phi; m_i, \lambda_\gamma}^{s\bar{s}}, \\
T_{m_f, m_\phi; m_i, \lambda_\gamma}^{uud} &= i T_0^{uud} \mathcal{S}_{m_f, m_\phi; m_i, \lambda_\gamma}^{uud},
\end{aligned} \tag{4}$$

where $m_{f,i}$, m_ϕ , and λ_γ are the spin projections in z -direction of the final (initial) proton, ϕ meson, and photon helicity, respectively, and

$$\begin{aligned}
T_0^{s\bar{s}} &\propto A^* B a_0 F_{s\bar{s}}(q_{s\bar{s}}) F_{uud}(0) V_{s\bar{s}}(p'), \\
T_0^{uud} &\propto -A^* B a_1 F_{s\bar{s}}(0) F_{uud}(q_{uud}) V_{uud}(q_\phi).
\end{aligned} \tag{5}$$

$F_\alpha(q_\alpha)$'s ($\alpha = s\bar{s}, uud$) are the Fourier transforms of the overlap integrals between spatial wave functions of the struck cluster α in entrance and exit channels with effective momentum q_α , which reduces to \mathbf{q}^2 in the non-relativistic limit. V_α is the momentum distribution function of cluster α . The explicit expressions of Eq. (5) are given in Ref. [12]. The spin structure functions are

$$\begin{aligned}
\mathcal{S}_{m_f, m_\phi; m_i, \lambda_\gamma}^{s\bar{s}} &= \sqrt{3} \lambda_\gamma \sum_{\varrho} \langle \tfrac{1}{2} m_f \ 1 \ \varrho \mid \tfrac{1}{2} m_i \rangle \\
&\quad \times \boldsymbol{\varepsilon}^*(m_\phi) \cdot \boldsymbol{\varepsilon}(\lambda_\gamma) \xi_{\varrho}^{s\bar{s}}, \\
\mathcal{S}_{m_f, m_\phi; m_i, \lambda_\gamma}^{uud} &= \sqrt{3} \sum_{j_c, m_c, \varrho} \langle \tfrac{1}{2} m_f - \lambda_\gamma \ 1 \ \varrho \mid j_c m_c \rangle \\
&\quad \times \langle j_c m_c \ 1 \ m_\phi \mid \tfrac{1}{2} m_i \rangle \xi_{\varrho}^{uud},
\end{aligned} \tag{6}$$

where

$$\begin{aligned}
\xi_{\pm 1}^{s\bar{s}} &= \pm \frac{1}{\sqrt{2}} \sin \theta_{p'}, \quad \xi_{\pm 1}^{uud} = \mp \frac{1}{\sqrt{2}} \sin \theta_{q_\phi}, \\
\xi_0^{s\bar{s}} &= \cos \theta_{p'}, \quad \xi_0^{uud} = \cos \theta_{q_\phi},
\end{aligned} \tag{7}$$

with the production angle θ_k in the laboratory frame.

The corresponding amplitudes in helicity basis can be obtained with the relation [23,24],

$$\begin{aligned}
H_{\lambda_f, \lambda_\phi; \lambda_i, \lambda_\gamma} &= (-1)^{1-\lambda_i-\lambda_f} \sum_{m_i, m_f, m_\phi} d_{m_i, -\lambda_i}^{1/2}(0) \\
&\quad \times d_{m_f, -\lambda_f}^{1/2}(\theta) d_{m_\phi, \lambda_\phi}^1(\theta) T_{m_f, m_\phi; m_i, \lambda_\gamma},
\end{aligned} \tag{8}$$

where θ is the c.m. scattering angle and $\lambda_{i,f,\phi}$ is the helicity of the target (recoil) proton and ϕ , respectively. Note that the knock-out amplitudes of Eq. (4) are purely imaginary, which means that the incoming photon is absorbed by the 5-quark component of the target proton, whereas the OPE contribution of Eq. (2) is purely real. The total photoproduction helicity amplitude H is then the sum, $H = H^{\text{VDM}} + H^{\text{OPE}} + H^{s\bar{s}} + H^{uud}$. Close inspection of the amplitudes reveals that each amplitude exhibits different helicity structure. In particular, at $|t| \sim |t|_{\min}$ (i.e., $\theta \rightarrow 0$), we have $H^\alpha \propto \Lambda_\alpha \delta_{\lambda_f, \lambda_i} \delta_{\lambda_\phi, \lambda_\gamma}$, where $\Lambda_{\text{VDM}} = i$, $\Lambda_{\text{OPE}} = 2\lambda_i \lambda_\gamma$, and $\Lambda_{s\bar{s}} = 2i\lambda_i \lambda_\gamma$, while H^{uud} is suppressed. This gives rise to a strong interference between H^{VDM} and $H^{s\bar{s}}$ at forward scattering region, while H^{VDM} and H^{uud} interfere strongly at large θ . The OPE amplitude H^{OPE} contributes incoherently to the unpolarized cross section

and the double polarization observables of our interest, while the interference of H^{VDM} and the knockout amplitudes gives very distinct contributions to the polarization observables.

Figure 3 gives, together with the data of Ref. [21], the unpolarized ϕ photoproduction cross sections $d\sigma/dt$ of various mechanisms at $W = 2.155$ GeV as functions of θ , assuming that the strangeness probability $B^2 = 1\%$ and $|a_0| = |a_1| = 1/\sqrt{2}$. One sees that the main contribution comes from VDM mechanism except at large θ , where uud -knockout dominates. Excluding this extreme limit, where the validity of VDM is suspected and the contributions from excited intermediate states are expected, VDM process dominates and the knockout contribution is small, so the unpolarized cross section is not sensitive to the small strangeness content of proton. The OPE contribution is also small compared with the VDM, even though it is comparable to or larger than that of the $s\bar{s}$ -knockout. This validates our choice of VDM parameters.

From the helicity amplitudes we can obtain various single, double, or triple polarization asymmetries [24]. It turns out that the single polarization asymmetries are not sensitive to the strange quark admixture of proton while some of double polarization asymmetries do. We focus only on beam-target asymmetry \mathcal{L}_{BT} here and the others will be reported elsewhere. For photon and target proton polarized along $\pm\hat{\mathbf{z}}$ and $-\hat{\mathbf{z}}$, respectively, where $\hat{\mathbf{z}} = \hat{\mathbf{q}}^*$, i.e., a longitudinal asymmetry, we have

$$\mathcal{L}_{\text{BT}} \equiv \frac{|H_{u,u;+,+}|^2 - |H_{u,u;+,-}|^2}{|H_{u,u;+,+}|^2 + |H_{u,u;+,-}|^2}, \quad (9)$$

where the subscripts u and \pm refer to unpolarized and $\lambda_{i,\gamma} = \pm\frac{1}{2}$ case, respectively. Shown in Fig. 4 are our results for \mathcal{L}_{BT} at $W = 2.155$ GeV. Since there is an uncertainty in the phase between VDM and knockout amplitudes, we give the results for four different choices for the signs of a_0 and a_1 while keeping $|a_0| = |a_1|$. We see that this polarization observable is useful to determine the phase and magnitude of a_0 . This conclusion holds also for the longitudinal beam-recoil asymmetry \mathcal{L}_{BR} . Unlike the unpolarized cross section, \mathcal{L}_{BT} strongly depends on the strangeness content of proton. Even with $B^2 = 0.25\%$, the difference with the (VDM + OPE) prediction is significant. In addition, at small θ the results are nearly independent of the phase of a_1 , while they are nearly independent of the phase of a_0 at large θ . This is because the uud - ($s\bar{s}$ -) knockout process is suppressed as compared with the $s\bar{s}$ - (uud -) knockout at small (large) θ region. It is found that the effect of OPE is small for this asymmetry.

In summary, we find that, with the use of a relativistic harmonic oscillator quark model, the direct knockout processes give a very distinct contribution to some of the double polarization observables in ϕ photoproduction as compared with those of diffractive production and one-pion-exchange processes. It indicates that measurements of double polarization observables would be very useful in probing the strangeness content of the proton. We also find that the contribution of the knockout mechanism is suppressed with increasing initial photon energy because of the strong suppression of form factors in the knockout amplitudes. Therefore, the optimal range of the initial photon energy to measure the $s\bar{s}$ component of proton is expected to be around 2–3 GeV. The presently available experimental data [25] are not sufficient to test this idea. New experiments at the current electron facilities are strongly called for. On the theoretical side, further studies on the model dependence of our

results are definitely needed. This applies not only to the hadron quark model but also to the microscopic description for VDM. The latter point could be very important since we find knockout contribution to be most distinct near the ϕ production threshold while the diffractive scattering is normally associated with large s and small t region. Lastly, in threshold production, the outgoing ϕ and proton move with a small relative momentum and the OZI avoiding rescattering processes deserve also to be studied.

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FIGURES

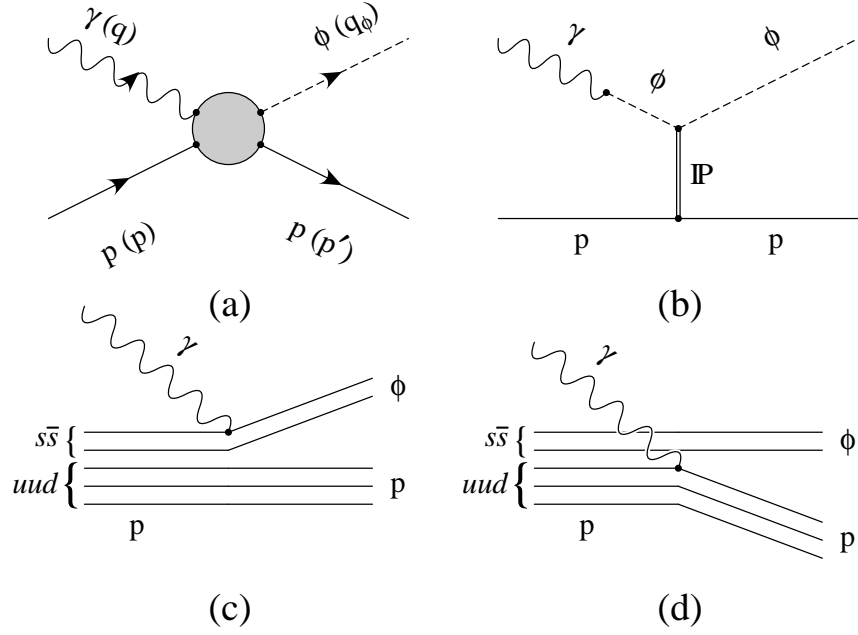


FIG. 1. (a) ϕ meson photo- and lepto-production from proton, where the photon would be virtual for the latter case. (b) diffractive ϕ production of vector-meson dominance model. (c,d) direct knockout mechanism to the ϕ production.

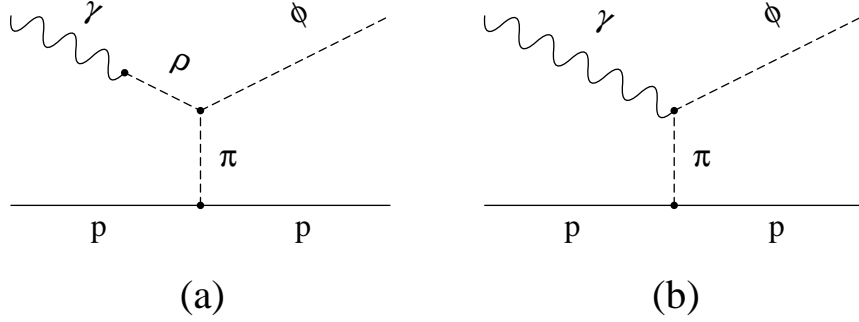


FIG. 2. One-pion-exchange model (OPE) of ϕ photoproduction.

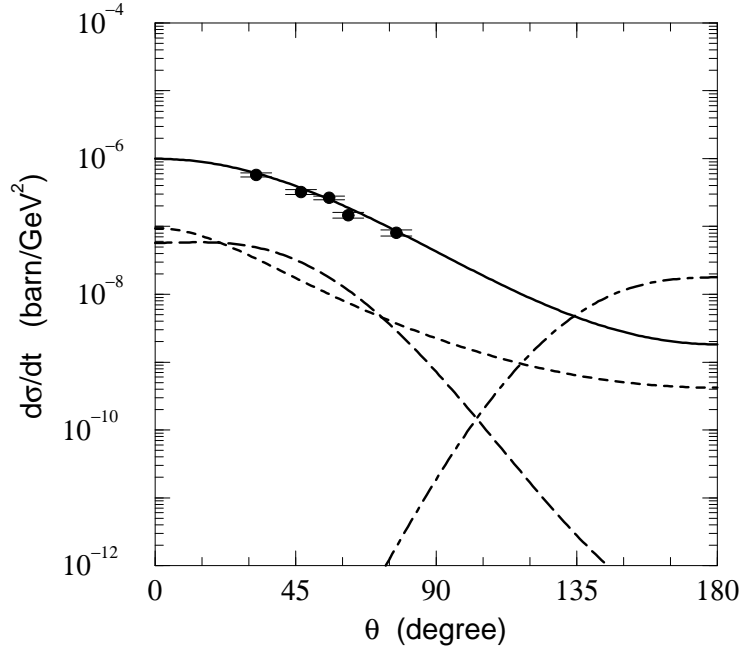


FIG. 3. The unpolarized photoproduction cross section $d\sigma/dt(\theta)$ at $W = 2.155$ GeV ($E_{\gamma}^{\text{lab}} = 2.0$ GeV). The solid, dotted, dashed, and dot-dashed lines give the cross section of VDM, OPE, $s\bar{s}$ -knockout, and $u\bar{u}$ -knockout with strangeness admixture $B^2 = 1\%$ and $|a_0| = |a_1| = 1/\sqrt{2}$. The experimental data are from Ref. [21].

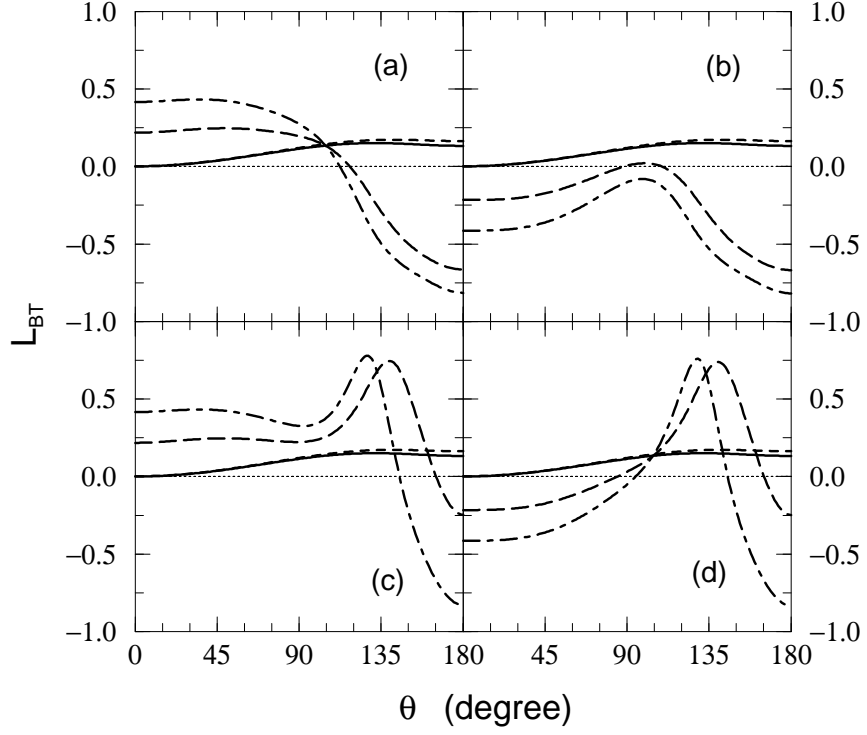


FIG. 4. The longitudinal asymmetry $\mathcal{L}_{BT}(\theta)$ at $W = 2.155$ GeV with $B^2 = 0\%$, i.e., the VDM and OPE (solid lines), 0.25% (dashed lines), and 1% (dot-dashed lines) assuming that $|a_0| = |a_1| = 1/\sqrt{2}$. The dotted line, which nearly overlaps the solid line, is the prediction of pure VDM. The phases of a_0 and a_1 for (a), (b), (c), and (d) are $(+, +)$, $(-, +)$, $(+, -)$, and $(-, -)$, respectively.